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EXPOSURE TO AIRBORNE ASBESTOS ASSOCIATED WITH SIMULATED CABLE INSTALLATION ABOVE A SUSPENDED CEILING*

D.L. Keyes[a]
J. Chesson[b†]
W.M. Ewing[c]
J.C. Faas[a]
R.L. Hatfield[d]
S.M. Hays[e]
W.E. Longo[f]
J.R. Millette[g‡]

[a]Environmental Sciences, Inc., 105 E. Speedway Blvd., Tucson, AZ 85705; [b]Chesson Consulting, Inc., 1717 Massachusetts Ave. N.W., Suite 601, Washington, DC 20036; [c]Diagnostic Engineering, Inc., 350 Franklin Rd., Suite 300, Marietta, GA 30067; [d]Law Associates, 114 Town Park Dr., Kennesaw, GA 30144; [e]Gobbell Hays Partners, Inc., 217 Fifth Avenue North, Nashville, TN 37219; [f]Materials Analytical Service, 3597 Parkway Ln., Suite 250, Norcross, GA 30092; [g]McCrone Environmental Services, Inc., 1412 Oakbrook Dr., Suite 100, Norcross, GA 30013

Installing cable above a suspended ceiling in the presence of asbestos-containing fireproofing is an example of an activity that may disturb in-place asbestos and associated dust and debris. Two simulations of cable installation were conducted in a room of an unoccupied school to test the extent of such disturbance and resulting elevations in airborne asbestos. Average airborne asbestos concentrations in the room increased over 500-fold during the simulations, with several samples exceeding 50 structures per cubic centimeter (s/cm³), as measured by transmission electron microscopy (TEM) with an indirect preparation technique. Elevated concentrations persisted during a subsequent cleaning of horizontal surfaces in the room and for several hours thereafter. Personal samples collected on the cable installers yielded TEM measurements averaging approximately 68 s/cm³ for the two simulations.

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†D ... sson is currently with the Australian Resource Assess- ... mmission, Queen Victoria Terrace, Canberra, ACT ..., Australia.

‡Dr. Millette is currently with Millette, Vander Wood and Associates, Inc., 5500 Oakbrook Parkway, Suite 200, Norcross, GA 30093.

Several studies have indicated that maintenance, repair, and construction activities in buildings with asbestos-containing material (ACM) can disturb the ACM and raise levels of airborne asbestos.[1–3] Installing electrical or computer cable above a suspended ceiling in the presence of asbestos fireproofing is a typical example of such activities. In-place fireproofing may be accidentally contacted and asbestos-containing dust and debris accumulated on ceiling tile may be disturbed. Resulting release or re-entrainment of asbestos fibers will likely lead to elevated levels of airborne asbestos. Although quantitative evidence of these effects is limited, a few studies have shown airborne fiber concentrations measured by phase contrast microscopy (PCM) to be over 50 fibers per cubic centimeters (f/cm³).[2] Most of these studies are not well characterized with respect to the type and duration of activities and the duration of elevated air levels. Moreover, transmission electron microscopy (TEM), rather than PCM, is now recognized as the method of choice to analyze air samples for asbestos.[4,5] TEM can distinguish between asbestos and nonasbestos fibers and can detect thin fibers that cannot be resolved by PCM. For these reasons, a controlled study of cable installation in the vicinity of asbestos fireproofing was undertaken.

The study was designed specifically to examine the effects of normal cable installation procedures without regard to the presence of asbestos. Accordingly, special precautions to minimize asbestos emissions were not taken. The study thus examines situations where workers do not know about the presence of asbestos or where they do not either know or use work practices

specially designed for work around asbestos. The authors' experiences working with owners of hundreds of buildings with ACM has indicated that these situations are not uncommon. The study re provide a rationale for using special work practices and ca /e to establish a baseline against which the effectiveness of these practices can be measured.

TEST SITE

The study was conducted in a 20-yr-old unoccupied school awaiting removal of the asbestos-containing fireproofing (Aspen Middle School in Aspen, Colo.). A room used for science education was selected as the test site (Figure 1). It contained a large

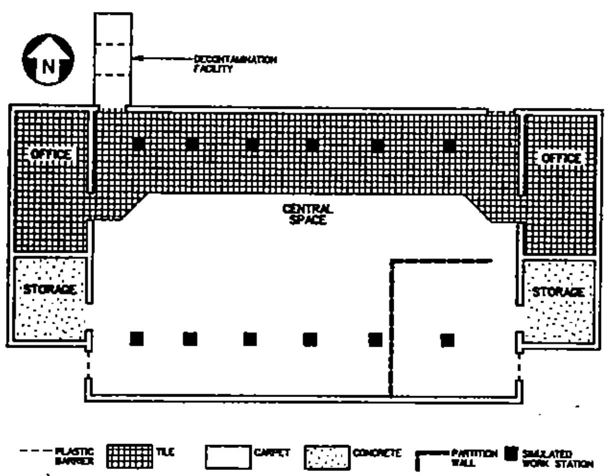

FIGURE 1. Diagram of the test site

central space, a separate area in one corner created by partitions extended to the suspended ceiling, and two office areas and two storage areas separated by masonry walls extending to the deck above. Total floor area was approximately 2000 ft^2. Floor coverings were carpet and vinyl tile. All movable furnishings had been removed before the start of the study.

Most of the room contained a suspended ceiling of 61 × 122 cm (2 × 4 ft) lay-in, asbestos-free tile; one office contained 30.5 × 30.5 cm (1 × 1 ft) hidden spline tile. Friable fireproofing with 15–20% chrysotile asbestos, 45–55% vermiculite, and 20–40% binder was sprayed on steel beams with overspray on the deck and utilities above the suspended ceiling. The fireproofing generally was in good condition. Some dust and debris similar in appearance to the fireproofing was visible on top of the ceiling tile. The space between the ceiling tile and the deck above was approximately 0.9 m (3 ft) in height and served as a return air plenum during normal building operations. This space had been entered a few times per year for utility system maintenance during the life of the building.

The room was prepared for the study by covering the doors and wall penetrations with 6-mil plastic sheets and duct tape. The HVAC sy was shut down and was to be demolished and replaced as pa ...ne subsequent asbestos abatement project. A three-chamber decontamination facility for personnel and equipment was constructed at one entry to the room, as shown in Figure 1.

STUDY DESIGN

Two identical simulations were performed. Each consisted of four phases: cable installation above the suspended ceiling (approximately 2.5 hr); an inactive period (approximately 1.5 hr); cleaning of horizontal surfaces in the room with a commercial vacuum cleaner, broom, and dry cloths (approximately 1 hr); and a final inactive period (about 3 hr). At the end of each 8-hr simulation, wet cloths and a high-efficiency particulate air (HEPA) vacuum cleaner were used to clean the floor and other horizontal surfaces and two HEPA air filtration units were used to clean the air.

To measure the effect of cable installation and subsequent cleaning of the test site, air samples were collected before each simulation began, during the installation activity, and at various times during the 6.5-hr postinstallation period. The experiment was designed to detect 10-fold or greater differences in average airborne asbestos levels among these periods with a probability of at least 95%. Assuming that the coefficient of variation for the TEM asbestos measurements would be approximately 100%, the number of samples was determined to be eight per period. Because the differences were actually much larger than 10-fold, it was not necessary to analyze all samples.

The quality assurance program included side-by-side samples and field and laboratory blanks. In addition, duplicate analyses of selected filters were performed by independent laboratories.

EXPERIMENTAL MATERIALS AND METHODS

Simulation Procedures

Cable was installed by using procedures typical of those used in the trade. From the northwest corner of the room, 12 separate cables were run to 12 simulated computer work stations, as illustrated in Figure 1. The simulation began by removing ceiling tile above each "work station" and as needed along the routes each cable would trace above the suspended ceiling. Altogether, about 15 out of roughly 200 individual tiles were moved. The removed tiles were then stacked on the floor. Working from ladders, installers attached a string weighted with a 2.54-cm (1-in.) nut to one end of each cable. The nut was then thrown in the direction of the appropriate work station. A second installer located the nut and pulled the string and cable to that location. This "throw and retrieve" operation was used to bring a cable to each work station. Typically, one or two throws were required for each retrieval. In the process, in-place fireproofing was struck about five times during the process of installing 12 cables. Figure 2 illustrates the installation process. All cables were then pulled back to the starting point, recoiled, and set aside, and all ceiling tiles were replaced. The entire operation of installing, removing, and recoiling cable is essentially equivalent to a 2.5-hr period of installation.

The cleaning operation consisted of vacuuming all carpeted areas; wiping all lab benches, window sills, and other horizontal surfaces with a dry cloth: and sweeping the tiled portion of the floor. No attempt was made to suppress re-entrainment of dust.

Equipment and Data Collection Methods

Air-sampling equipment used during the study included high-sampling pumps (Dawson Associates, Tucker, Ga.) and personal sampling pumps (Mine Safety Appliance Company, Pittsburgh, Pa.). Flow measurements were performed on-site with a Mini-Buck™ Model M-30 automated soap bubble calibrator (A.P. Buck, Orlando, Fla.). The sampling media consisted of 0.45-µm pore size mixed cellulose ester filters housed in 25-mm sampling cassettes (Nuclepore Model SN32275, Cambridge, Mass.). Other equipment used during the study included a HEPA vacuum cleaner (Hako Minuteman™, Addison, Ill.), HEPA air filtration units with nominal flow rates of 1950 ft^3/min (Model Mach 2, Critical Systems, Houston, Tex.), a Dial-a-matic™ upright vacuum cleaner (Hoover Vacuum Cleaners, North Canton, Ohio), and various personal respirators. Number 16/3 electrical cord was used as the computer cable.

FIGURE 2. Cable installation process

The flow rate of each air-sampling pump was measured before and after each experiment. High-flow pumps were placed at various locations both inside and outside the room, as shown in Figure 3. Personal pumps were placed on selected workers.

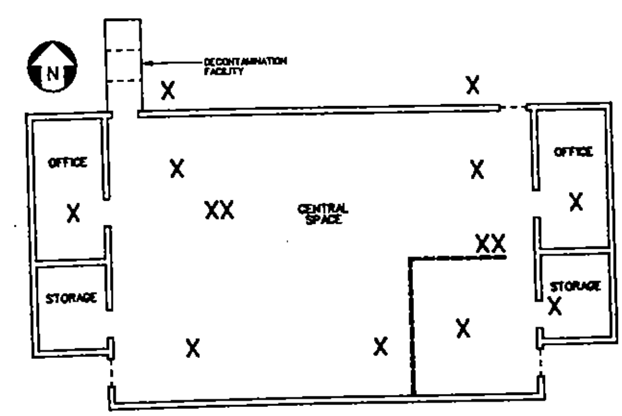

FIGURE 3. Location of stationary air-sampling pumps

Airflow rates were approximately 5.4–8.1 L/min for the high-flow pumps and 1.9 L/min for the personal pumps. Overloading of filters during the simulations required changes of cassettes on each pump. All cassettes were taped closed and transported by one of the authors to the laboratories for analysis.

Asbestos Analysis

Subsets of area and personal samples were selected to reflect a wide spatial distribution within the room. Each of the selected samples was analyzed by TEM. Because the filters were heavily loaded, they were prepared for analysis by TEM with an indirect rather than a direct technique. Direct sample preparation, such as required for asbestos abatement projects in schools (Asbestos Hazard Emergency Response Act—40 CFR 763), is appropriate for measuring low concentrations of airborne asbestos in relatively clean environments. A quantitative measure of the limitations of direct TEM preparation is provided by the National Institute for Occupational Safety and Health (NIOSH) for Method 7402—the upper boundary of airborne asbestos concentrations that can be reliably measured is 0.5 f/cm^3.[6] Where asbestos concentrations are high or the air is heavily contaminated with nonasbestos particles, obscuration of asbestos fibers by other fibers or by nonasbestos particles reduces the reliability of fiber counting.[7,8] Indirect sample preparation includes filter ashing to remove organic materials, followed by water suspension, sonication to mix the ashed material, and refiltering. Suspension, sonication, and refiltering allows for dilution of the sample as needed and more even distribution of fibers for TEM viewing, both of which improve the reliability of fiber counting.[7,8]

The indirect method of sample preparation and microscope counting rules as described in the Yamate method, Level II[9] were employed with one exception—sonication time was 10 min

ather than 3 min. Either one-ourth or one-eighth of each filter lepending on the degree of dust oad was ashed in a plasma the. e ashed material was ien suspended in distilled 'ater, sonicated, refiltered, and iounted for TEM examination y using the Jaffe-Wick method. ll asbestos structures that could ; resolved were reported.

Personal samples were also ialyzed by PCM. NIOSH Meth-1 7400 was used with the "A" unting rules.[10]

TABLE I. Descriptive Statistics of TEM Results for the First Simulation

Phase	*Arithmetic Mean (s/cm^3)*	*Arithmetic Std. Dev. (s/cm^3)*	*Geometric Mean*	*Number of Observations*
Before installation	0.052	0.030	0.046	5
During installation (area samples)	28.9	12.6	26.9	5
During installation (personal samples)	10.5	11.6	7.1	3
After installation	8.4	7.0	6.2	6

TABLE II. Descriptive Statistics of TEM Results for the Second Simulation

Phase	*Arithmetic Mean (s/cm^3)*	*Arithmetic Std. Dev. (s/cm^3)*	*Geometric Mean*	*Number of Observations*
Before installation	0.158	0.094	0.129	5
During installation (area samples)	100.2	91.9	67.4	4
During installation (personal samples)	124.8	85.6	102.7	3
After installation	17.0	13.5	12.3	4

Statistical Analysis

Where there were two or more nsecutive samples at a particular cation during a given sampling riod, a time-weighted average as calculated so that all measurements of airborne asbestos concentrations are based on equivalent ne periods. Statistical analyses were applied to the logarithm ase 10) of the measured concentration. The log transformation nds to equalize variances and permit the use of standard statistical sts would otherwise be inappropriate. Previous studies of do pollution have demonstrated that air pollution data tend be lognormally distributed.[11]

The effect of "sampling period" as a variable was tested with standard one-way analysis of variance and pairwise comparins between individual sampling periods were performed by ing the Scheffé test.[12] Results are expressed as p-values. The aller the p-value, the stronger the evidence for a difference tween the sampling periods being compared. P-values less in 0.05 are usually regarded as statistically significant.

Ratios of airborne asbestos concentrations and their 95% nfidence intervals were estimated by calculating the ratio of corresponding sample geometric means. Geometric as opsed to arithmetic means are the appropriate quantities to use estimate the ratio when the distributions are lognormal and the efficients of variation are equal.

RESULTS

ble I shows the results for the area samples for the first nulation. The average concentration of airborne asbestos (as asured by TEM) during the cable installation operation is imated to be 590 times higher than the concentration bee the experiment began (geometric means of 26.9 and 0.046 m^3). The 95% percent confidence interval (CI) for this ratio is) t 0. Likewise, the average concentration during the stin ation period is 140 times higher than before the experint began (CI = 50 to 330). Both these differences have a alue (p) of less than 0.0001. The concentration during cable installation is over four times higher than during the postinstallation period (CI = 1.8 to 11, p = 0.01).

Table II reveals similar patterns for the second simulation. Average airborne asbestos concentrations during cable installation are 520 times higher (67.4 versus 0.129 s/cm^3) than those before the experiment began (CI = 140 to 1950, $p < 0.0001$) and those during the postinstallation period are 95 times higher than those before (CI = 25 to 360, p = 0.0001). The ratio of average concentration during cable installation to average concentration during the postinstallation period is over 5 (CI = 1.4 to 22, p = 0.12), but the difference is not statistically significant at the 0.05 level.

Tables I and II also show the TEM results for the personal samples during cable installation for each of the two simulations. The relationship between area and personal samples differs between simulations. In the first simulation, the average concentration measured by area samples during installation is higher than the concentration measured by personal samples (p = 0.04). In the second simulation, the average concentration measured by area samples during installation is lower, but the difference is not statistically significant at the 0.05 level (p = 0.6). Nevertheless, both the area and personal samples are significantly elevated compared with the levels prior to cable installation.

Figure 4 summarizes the results for the two simulations. Note that the vertical axis is on a logarithmic scale. The average levels of airborne asbestos (geometric means, or means on the log scale) are represented by the height of each bar for each of the three phases of the experiments. The variation about the mean (standard deviation on the log scale) is indicated by the vertical lines. Also shown are the means and standard deviations of the personal samples during the installation and postinstallation periods.

A few personal samples collected during cable installation were also analyzed by PCM for comparison purposes. The

arithmetic means are 0.13 f/cm^3 (SD = 0.03) for the first simulation and 0.34 f/cm^3 (SD = 0.11) for the second simulation.

The quality assurance results indicated that field and laboratory tamination was minimal with one exception. Of the 13 field and oratory blanks analyzed, 1 field blank showed a higher than expected structure loading (441 s/mm^2). The laboratory blanks averaged 35 s/mm^2 and the field blanks averaged 151 s/mm^2.

Initial comparison of side-by-side samples analyzed by two independent laboratories showed substantial differences in results. Investigation of these results suggests that differences in sample preparation and analysis—time of sonication, size of the filter used for refiltration of the ashed sample, and failure of one laboratory to count small asbestos structures (less than 0.5 μm in length)—accounts for many of these differences, in addition to any inherent difference in the air sampled between side-by-side samples. To further test this conclusion, the quality assurance laboratory reanalyzed a different portion of the same filter (to avoid differences between side-by-side samples) for six stratified random samples, holding constant the sonication time, filter size, and structure counting variables. Although the second laboratory produced results that were approximately half as large as those of the first laboratory, there was a high and statistically significant correlation (0.88, $p = 0.02$) between the two sets of results.

DISCUSSION

The results show that airborne asbestos concentrations as measured by TEM are significantly elevated during cable installa-. Concentrations generated during the study were high both ative to concentrations before the experiment and in absolute terms. Concentrations peaked during installation. Whether cleaning activities resuspended asbestos structures and thereby contributed to the elevated levels after cable installation cannot be determined directly from the data. However, elevated concentrations persisted for several hours after the installation was finished.

For the personal samples, asbestos concentrations measured by TEM are substantially higher than might be expected from the fiber levels recorded by PCM. This suggests that most of the measured asbestos structures are thinner than the resolution limit of PCM or shorter than those fibers counted according to NIOSH Method 7400. An examination of fiber size distributions reported for the

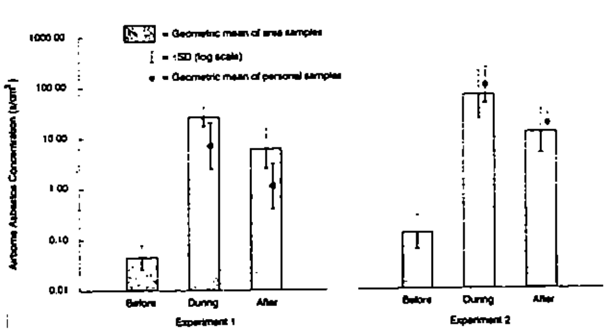

FIGURE 4. Summary of TEM results

TEM analyses verifies this conclusion—over 95% of measured structures are thinner than 0.25 μm and shorter than 5 μm.

Health scientists continue to debate the relationship between fiber size and potency; the arguments have recently been summarized by Chesson et al.[13] The current Occupational Safety and Health Administration (OSHA) exposure standards are based on measurements that use NIOSH Method 7400 (or equivalent) and thus on fibers longer than 5 μm and with diameters greater than about 0.25 μm. However, these fiber dimensions do not reflect an official OSHA view of the health question; rather, they derive from historical considerations of fiber counting reliability.[14] OSHA recognizes that PCM is neither specific for asbestos nor sensitive to small (both short and thin) fibers; in this light, PCM measurements are best viewed as an indicator of exposure to airborne asbestos. How adequate an indicator PCM measurements are depends in part on the health significance of the small, unmeasured fibers. Research continues on the question.

The analytical method used in the present study measures asbestos structures of all sizes. The term "structures" is used to identify free asbestos fibers, overlapping fibers identified as "bundles" and "clusters," and fibers combined with matrix materials called "matrices." Moreover, sonication of ashed samples may disassociate bundles and clusters and disassemble matrices, thereby increasing the total number of structures counted.[15] (Some have suggested that sonication may actually break individual asbestos fibers but this hypothesis does not accord with available evidence.[15])

The significance of the elevated concentrations of airborne asbestos recorded in the present study will depend on the physiological importance of the asbestos structures identified and counted. One could argue that the disassociation and disassembly of complex structures during sonication mimics natural physiological processes in the human lung.[16] Thus, indirect preparation of TEM samples not only improves fiber counting reliability, it may provide a better measure of asbestos fibers presented to the lung. However, research is needed to substantiate this possibility.

Despite the remaining uncertainty about the significance of small asbestos fibers and the disassembly of complex structures during indirect sample preparation, cable installation workers are well advised to wear respirators and to use work practices designed to reduce fiber release and resuspension. The recorded concentrations of airborne asbestos are high even if only 5% of the structures are ultimately shown to have health consequences. The persistence of high asbestos levels during the simulation suggests that work areas should be isolated from the rest of the building and the air cleaned with air filtration units before the areas are reoccupied, unless use of wet methods and good work practices can greatly reduce concentrations of airborne asbestos.

The extensive quality assurance aspects of this study identified two potential problems. The first involves possible contamination of samples. The one blank sample with an elevated reading (441 s/mm^2) suggests that contamination may have contributed to the observed levels of airborne asbestos. However, only one of three field blanks showed elevated loadings and none of the background samples showed unexpectedly high levels. Moreover, even if contamination was widespread, a structure

oading of 441 s/mm^2 is low compared to the loadings on all but he background samples (the average loading was approximately 18 000 s/mm^2 for samples collected during the simulation. Thus, or ation is not believed to be a problem.

second potential problem concerns interlaboratory dif- erences in analytical results. Although the investigation identi- ied the major causes of the discrepancies, the quality assurance aboratory's results were still approximately one-half as large as he primary laboratory's results. However, the high correlation etween the two sets of results means that the study's conclusions vould be unchanged regardless of which laboratory analyzed the amples. Systematic differences between laboratories is prob- bly not unusual for TEM analysis of asbestos in air; the authors' bservations suggest that studies involving airborne asbestos neasurements should utilize data from more than one laboratory. Other investigators are encouraged to conduct similar quality ssurance examinations and to probe the causes of any observed nterlaboratory differences.

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